DEVELOPMENT OF HIGH-SPEED PHOTODIODE MODULES FOR OPTICAL COMMUNICATIONS

SAKAKIBARA Katsutoshi *1   *KOBAYASHI Fumihiko* *2   *WADA Morio* *1

This paper describes the structure and characteristics of photodiode modules developed for fiber-optic communications. The modules consist of a highly responsive GaInAs PIN photodiode with high-speed response, and are assembled using YAG laser welding. A responsivity as high as 0.5 A/W and a cutoff frequency higher than 20 GHz have been achieved at a wavelength of 1.55 μm by using this specially designed module structure.

INTRODUCTION

The development of increasing transmission rates for optical fiber communication has proceeded. Systems with transmissions of up to 2.4 Gb/s have already been brought about and even a system transmitting at 10 Gb/s has been put into practical use. Such long-distance communications have been realized using fiber-optic amplifiers and high responsive, high-speed receivers. At the same time, more superior receivers are necessary for the instruments used in maintaining both fiber-optic communications systems and monitoring systems. To meet this demand, high responsive, high-speed photodiode modules with a cutoff frequency of more than 20 GHz have been developed using the accumulated laboratory technology of compound optical semiconductor device processes.[(1) (2) (3)] This paper describes the structure and characteristics of photodiode modules. Figure 1 is a photograph of the YR15-series and Figure 2 is a photograph of the YC1020 O/E converter.

*1 Optoelectronics Laboratory, Corporate R&D
*2 EDA Center

DEVICE DESIGN

The developed optical receiver is a top-illuminated PIN photodiode, easy-coupled to fibers. The key points to keep in mind in order to realize both high responsivity and high speed are:

1. To reduce both stray capacitance and inductance
2. To deplete the light-absorbing layer to reduce the diffusion current
3. To prevent trapping of the photo carrier generated in the light-absorbing layer at the hetero-junction

Figure 1 YR15 Photodiode Module

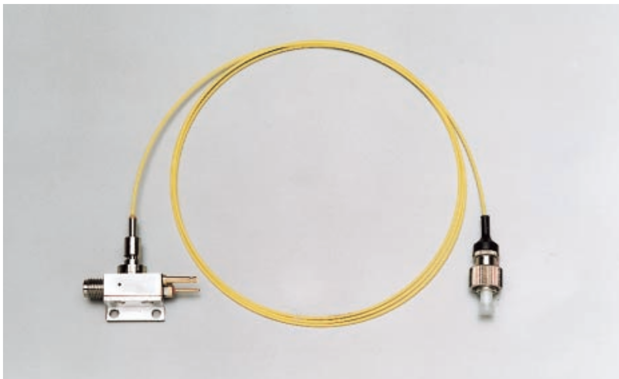


Figure 2 YC1020 O/E Converter

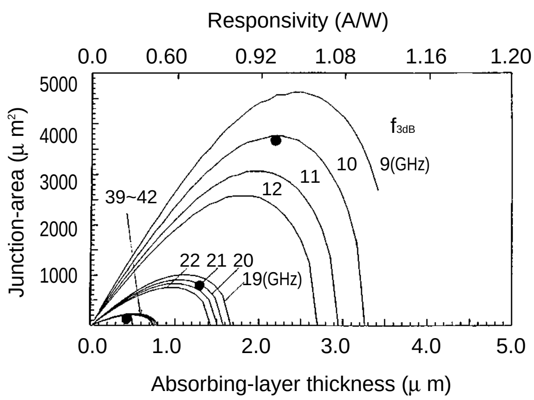


Figure 3 Contours of Cutoff Frequency in the PN Junction Area by the Light Absorption Layer Plane

4. To select the optimal light-absorbing layer thickness because of the tradeoff between high responsivity and high-speed.

Theoretically the cutoff frequency is calculated to optimize the device structure.

The cutoff frequency is calculated by equation (1).(4) This equation assumes that 1 to 3 are realized and assumes that carrier transverses the light-absorbing layer with the saturation velocity.

$$\left| \frac{i_0(\omega)}{i_0(0)\,(1+j\omega CR)} \right| = \frac{1}{2} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

$$\frac{i_0(\omega)}{i_0(0)} = \frac{1}{(1-e^{-\alpha L})}\left[\frac{(1-e^{-j\omega\tau_n-\alpha L})}{(j\omega\tau_n+\alpha L)} + e^{-\alpha L}\frac{(e^{-j\omega\tau_n}-1)}{j\omega\tau_n} + \frac{(1-e^{-j\omega\tau_p})}{j\omega\tau_p} + e^{-\alpha L}\frac{(1-e^{\alpha L-j\omega\tau_p})}{(\alpha L-j\omega\tau_p)}\right]$$

$\tau_n = L/\nu_n$, $\tau_p = L/\nu_p$, $C = \varepsilon_s\varepsilon_o S/L$

$i_o(\omega)$, $i_o(O)$: Optical current of photodiode

ω : Angular modulation frequency, R : Load resistance (= 50Ω)

C : PN conjunction capacitance

α : Absorption coefficient (0.66 μm^{-1} @ wavelength 1.55 μm)

L : Absorption layer thickness, S : PN junction area

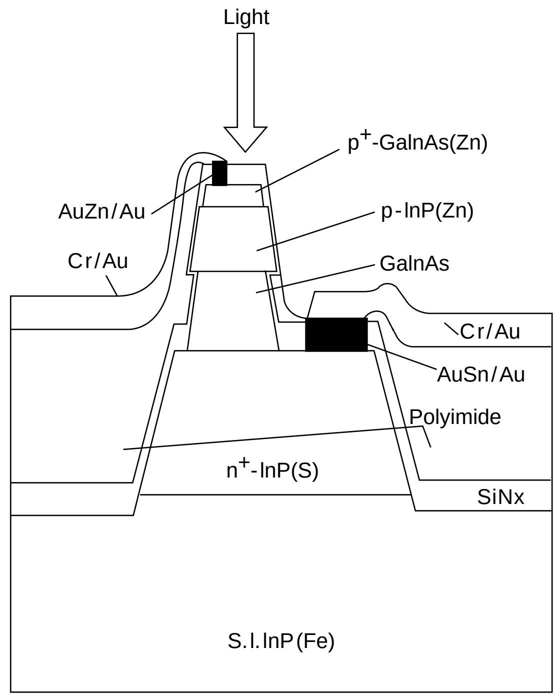


Figure 4 Schematic Diagram of Cross Section of PIN Photodiode

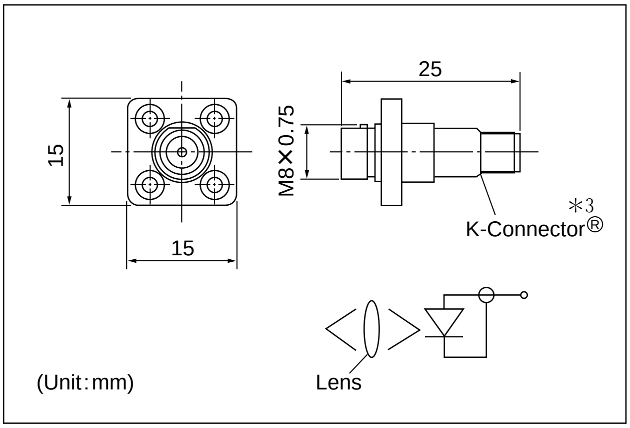
ν_n : Electron saturation velocities (6.5×10^4 m/s)

ν_p: Hole saturation velocity (4.8×10^4 m/s)

ε_s : Relative dielectric constant (14.1), ε_o: permitivity of free space

Figure 3 shows the contours of the constant cutoff frequency in the p-n junction area, light-absorbing-layer-thickness (depleted) plane. The thicker the light-absorbing layer, the lower the cutoff frequency because the cutoff frequency is limited by the carrier transit time. The larger the p-n junction area, the lower the cutoff frequency because of the limitation of the RC time constant determined by the junction-capacitance. At the same time, the thicker the light-absorbing layer, the higher the responsivity. The plots in the figure are the data for a prior device's prototype. From Figure 3, it is clear that responsivity must be sacrificed somewhat in order to obtain the required cut-off frequency. The typical method for solving this problem is to use a wave-guide photodiode (5) or a back-illuminated photodiode with a lens(6). However, these types of diodes have a disadvantage in that their diode constructions and packaging mechanisms are complicated.

Since a top-illuminated photodiode still has a sensitivity of at least 0.5 A/W when the cut-off frequency is around 20 GHz, this type of photodiode is employed in our modules. Figure 4 shows a schematic cross section of the PIN photodiode. In order to reduce stray capacitance, mesa islands on a semi-insulated substrate are passivated with polyimide. In order to deplete the light-absorbing layer with a low bias voltage, the concentration of the carrier of the light-absorbing GaInAs layer is reduced to 1×10^{15} cm^{-3}. In



*3 Resistered Trademark of WILTRON, Inc.

Figure 5 Outline of YR15 Series Module

Table 1 YR15 Series Specifications (25°C, TYP.)

Parameter	Symbol	Test Cond.	YR1520R	YR1510R	Unit
Cutoff Frequency (1)	fc	V_R=5V, λ=1.54 μm	20	10	GHz
Responsivity (2)	R	V_R=0V, λ=1.54 μm	0.5	0.9	A/W
Dark Current	I_D	V_R=5V	10	10	nA

(1) Referred to 1GHz responsivity. (2) Using single mode fiber

Table 2 YC1020 Series Specifications (25°C, TYP.)

Parameter	Symbol	Test Cond.	YC1020	Unit
Bandwidth (3)	B	V_R=5V, λ=1.54 μm	DC-20	GHz
Conversion Gain (2)	G	V_R=5V, λ=1.54 μm	12.5	V/W
Input Return Loss	L_I	λ=1.54 μm	30	dB
Output Return Loss	LO		5	dB
Noise Equivalent Power	P_N		30	pW/√Hz

(3) Referred to 0.5 GHz responsivity.

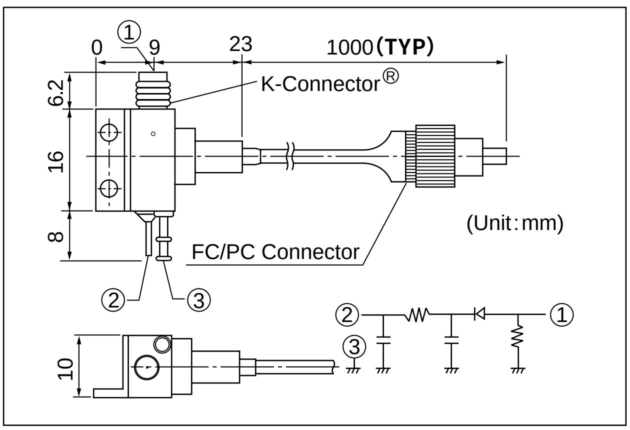


Figure 6 Outline of YC1020 Converter

order to prevent trapping of the photo carrier generated in the light-absorbing layer at the hetero-junction, a p-n junction is formed in the light-absorbing layer.

PACKAGING

In order to increase accuracy and improve reliability, YAG laser-welding is adopted to assemble the modules. Figure 5 shows the dimensions of the YR15-series. Both photodiode and output connector are connected on the submount. Since optical focusing is done through the GRIN lens fixed to the fiber receptacle, the photodiode is placed in this focus by adjusting its position on the sub-mount. After that, the photodiode is fixed to the submount by means of YAG laser welding. The YC1020 consists of a photodiode-terminated 50 Ω and a DC bias circuit, and incorporates a single-mode fiber, and is assembled by YAG laser-welding (Figure 6).

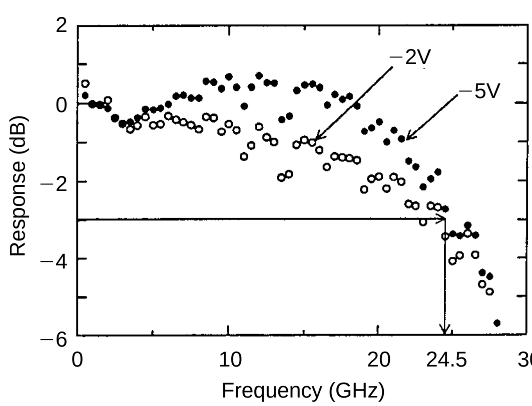


Figure 7 Frequency Response of YR1520 Module

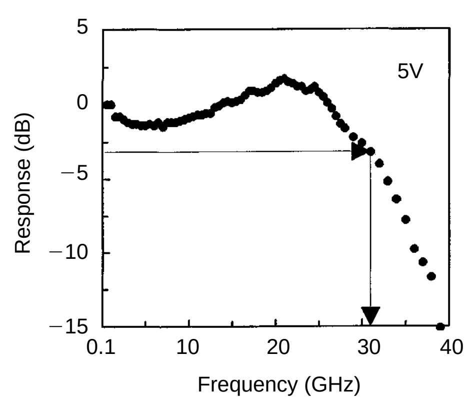


Figure 8 Frequency Response of YC1020 Converter

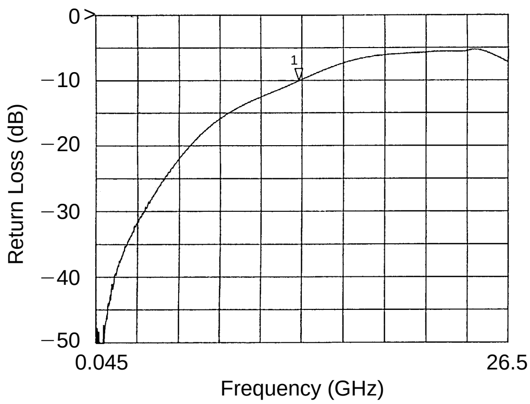


Figure 9 Return Loss S_{11} of YC1020

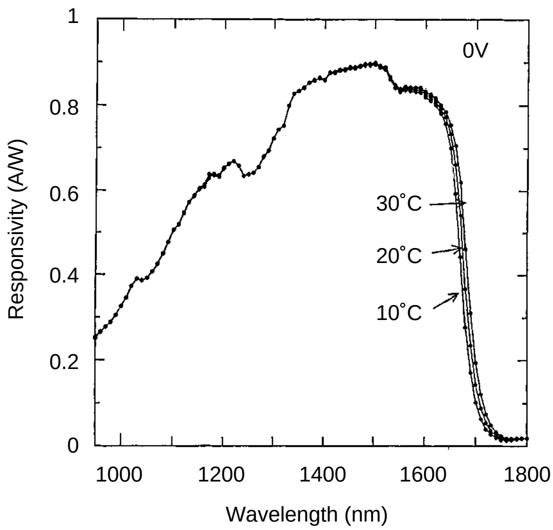


Figure 10 Responsivity of YR1510

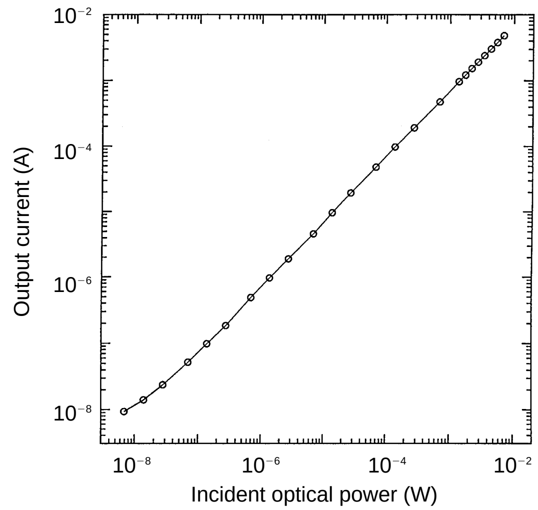


Figure 11 Linearity of YR1520

CHARACTERISTICS

Tables 1 and 2 show the specifications for both the YR15 and YC1020 series. Figures 7 and 8 show the frequency responses of the YR1520 and YC1020 by means of optical heterodyne detection. [7] In both modules, a cutoff frequency of more than 20 GHz at a low operating voltage of 5-V inverse voltage and a responsivity of more than 0.5 A/W using a single-mode fiber are achieved. Figure 9 shows return loss S_{11} of the YC1020. Figure 10 shows a responsivity ranging from 0.95 to 1.7 µm in the YR1510, and a responsivity is very high in the range of 1.3 to 1.6 µm. Figure 11 shows the linearity of the YR1520. It is possible to operate up to 7 mW. Further, after an HBT (85°C, 5 V, 1000 h) test, the characteristics satisfy the specifications.

CONCLUSION

In this paper, modules (the YR15-series and the YC1020) with a high speed (>10 GHz) and high responsivity (>0.5A/W) in optical communications have been presented. We hope the modules can be applied to optical communications and optical instruments. We will improve their reliability and function. ◆

REFERENCES

(1) WADA M. et al., “Photo-detectors for Near-Infrared Spectroscopy,” Yokogawa Technical Report, No. 22, pp. 5 to 8 (1996)

(2) INOUE T. et al., “Rib-Waveguide Distributed-Feedback Semiconductor Lasers,” Yokogawa Technical Report, No. 20, pp. 1 to 4 (1995)

(3) SAKAKIBARA K., WADA M. AND SEKIGUCHI Y.: “High-speed GaIn PIN Photodiodes with Low Series Resistance, “ Jpn. J. Phus. Vol. 31, pp. 1807 to 1809 (1992) Part 1

(4) BOWERS J. E. and BURRUS C. A. Jr.: “Ultrawide-band Long Wavelength p-i-n Photodetectors, “ J. Lightwave Technol. Vol. LT-5, No. 10, pp. 1339 to 1350

(5) KATO K., HATA S., KAWANO K. and KOZEN A., “A High Efficiency 50 GHz InGaAs Multimode Waveguide Photodetector,” IEEE J. Quantum Electron, Vol. 28, No. 12, pp. 2728 to 2735 (1992)

(6) MAKIUCHI M., WADA O., KUMAI T., HAMAGUCHI H., AOKI O. and OIKAWA Y.: “Small-Junction-Area GaInAs/ InP pin Photodiode with Monolithic Microlens,” Electron, Lett., Vol. 24, No. 2, pp. 109 to 110 (1988)

(7) KAWANISHI S., TAKADA A. and SARUWATARI M.: “Wide-band Frequency Response Measurement of Optical Receivers Using Optical Heterodyne Detection,” J. Lightwave Technol., Vol. LT-7, No. 1, pp. 92 to 98 (1989)